Insect Infestation of Stored Oats in Florida and Field Evaluation of a Device for Counting Insects Electronically

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J. Econ. Entomol. 93(3): 1035–1044 (2000)

ABSTRACT Automated methods of monitoring stored grain for insect pests will contribute to early detection and aid in management of pest problems. An insect population infesting stored oats at a seed processing plant in north-central Florida was studied to test a device for counting insects electronically (Electronic Grain Probe Insect Counter, EGPIC), and to characterize the storage environment. The device counts insects as they fall through an infrared beam incorporated into a modified grain probe (pitfall) trap and transmits the counts to a computer for accumulation and storage. Eight traps were inserted into the surface of the grain bulk, and the insects trapped were identified and counted manually at weekly intervals. Grain temperature and moisture content also were recorded for each trap location. Manual and automatic counts were compared to estimate error in the EGPIC system. Both over- and undercounting occurred, and errors ranged from −79.4 to 82.4%. The mean absolute value of error (±SE) was 31.7% (±4.3). At least 31 species, or higher taxa, were detected, but the psocid *Liposcelis entomophila* (Enderlein) and the foreign grain beetle, *Ahasverus advena* (Waltl), accounted for 88% of the captured insects. Species diversity, phenology, and spatial distribution are presented, as well as temporal and spatial distribution of grain temperature and moisture content. The data sets generated will find application in population modeling and development of integrated pest management systems for stored grain.

KEY WORDS stored-grain insects, phenology, species diversity, spatial distribution, trapping, electronic monitoring

AUTOMATED METHODS OF monitoring stored grain for insect pests will contribute to early detection of infestation and aid in management of pest problems. Electronic devices designed for this purpose must be able to withstand the rigors and overcome the challenges of commercial storage environments, but the exact nature of these requirements is unclear. Mathematical modeling of insect populations and other features of stored grain ecosystems will provide robust tools for developing and evaluating new control strategies with minimum reliance on chemical pesticides, but data sets adequate to support modeling are scarce, especially for the warm and humid southeastern states, where the potential for serious insect problems persists throughout the year. Arbogast and Throne (1997) provided partial characterization of the stored corn ecosystem on farms in this region, with special reference to South Carolina, and pointed out the need for full characterization of various storage habitats to model the diverse conditions that exist in marketing channels. The current article reports a study of stored oats in north-central Florida, the primary purpose of which was to test a device for counting insects electronically (Electronic Grain Probe Insect Counter, EGPIC) and to characterize the storage environment. Small segments of this study were published earlier for the purpose of illustrating spatial analysis (Brenner et al. 1998, Arbogast and Mankin 2000). The phenology and spatial distribution of *Typhaea stercorea* (L.) on wheat stored in the same bin a year later was described by Arbogast et al. (2000).

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Materials and Methods

Storage Situation. During the summer of 1996, we studied an insect infestation of stored oats at a seed processing plant in north-central Florida (Williston, Levy County). About 36 t (2,480 bu) of oats, which had been harvested in May and held under cover in field carts until 25 June, were placed in a galvanized steel bin (5.5 m high, 5.5 m diameter) and fumigated with phosphine 2 d later. The bin was equipped with an aeration duct and perforated floor, but the aeration fan was not installed. Fumigation was done by placing pellets of aluminum phosphide on the grain surface and in the aeration duct, which was then sealed. A second fumigation was done in the same manner on 15 September.

Grain Temperature and Moisture Content. Grain temperature and moisture content were measured at eight points near the surface of the grain bulk (Fig. 1A). Temperature was recorded every 72 min with RD-TEMP-XT temperature loggers (Omega Engi-

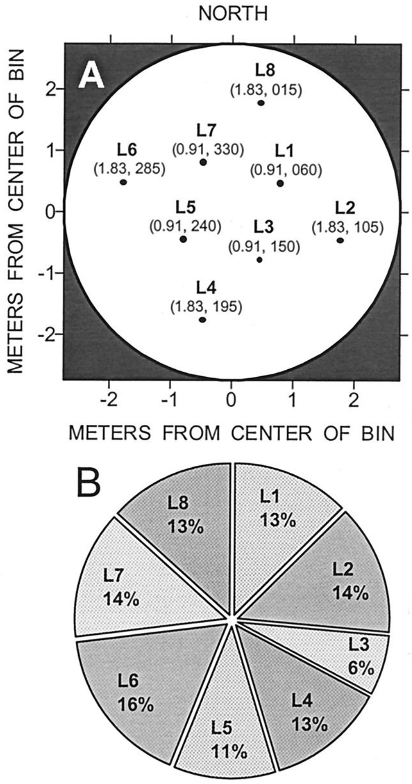

Fig. 1. (A) Points in the grain bulk at which temperature sensors and pitfall traps were located and from which grain samples were taken to determine moisture content. These points were fixed with reference to the center of the storage bin, and their locations were specified in polar coordinates (r, θ), where r is distance in meters from the center and θ is the compass bearing (degrees clockwise from north). Each point is numbered and its coordinates are given in parentheses. (B) Distribution of insects captured, by trap location.

neering, Stamford, CT) for later downloading to computer storage. These were installed on 17 July, when phosphine level in the head space of the bin had declined to <0.1 ppm. Each logger had an external temperature probe that was secured with tape to a dowel rod (38 cm long, 1.8 cm diameter) bluntly pointed at one end. The rods were pushed into the grain so that the sensor, which rested in a shallow groove near the pointed end, was 18 cm below the surface. The logger itself was held in a plastic zip lock bag attached to the exposed end of the dowel rod. On 24 July, we began taking grain samples at weekly intervals for measurement of moisture content. A 0.5-liter sample of grain was taken from the surface adjacent to each temperature probe. The samples were held in sealed polypropylene jars (for <24 h) until moisture content could be measured with a Motomco model 919 Grain Moisture Tester (Dickey-John, Auburn, IL). Descriptive statistics for the 72-min temperature records and weekly moisture content measurements at each location, and for all locations combined, were calculated with the SAS Univariate Procedure (SAS Institute 1988), and displayed as box plots with SigmaPlot 5.0 (SPSS 1998). In addition, daily and weekly means ± SE were determined over all locations.

Trapping. On 17 July, at the same time we installed the temperature equipment, we placed eight polyethylene grain probe traps just below the grain surface, one adjacent to each temperature probe (Fig. 1A). These traps were of the type described by Barak et al. (1990), with the slant of the holes reversed (Subramanyam et al. 1989), and each incorporated the automatic insect counter (EGPIC) described by Shuman et al. (1996). The automated trap counted insects as they fell into the pit and transmitted the counts to a computer for accumulation and storage. Insects were removed from the traps at weekly intervals and stored in alcohol until they could be identified and counted in the laboratory. Data were collected over a period of 12 wk, but are missing for weeks 9 and 10 because all traps and temperature sensors were removed just before the second fumigation and the bin was not reentered for 2 wk. The manual counts provided measures of species diversity, phenology, and spatial distribution, as well as a means for testing the accuracy of the automatic totals (all species) gathered by EGPIC. Spatial distribution of manual counts was examined by contour analysis (Arbogast et al. 1998), using Surfer 6.02 (Keckler 1995) with radial basis functions for interpolation. This is a flexible algorithm that provides good overall interpretation of most data sets (Keckler 1995). Trap counts of all species with sufficient representation in the insect population, as well as total beetle counts, were analyzed spatially, and representative examples are presented.

Evaluation of EGPIC. Manual and automatic counts were paired by week and location in the bin. Every pair can be regarded as independent of every other pair; thus the measured pairs can be considered a random sample of all possible pairs. Errors in automatic counts were expressed as percentages of the manual counts: Error = 100 (manual − automatic)/manual. Before calculating any statistics, three observations were deleted (two from week 7 and one from week 8) because of suspected malfunctions in the automatic insect counter. The Wilcoxon Signed Rank test, run under the SAS Univariate Procedure (SAS Institute 1988), was used to test the null hypothesis that the mean difference between manual and automatic counts was 0. Box plots were done with SigmaPlot 5.0 (SPSS 1998), and regression analysis of manual versus automatic counts was done with the SAS Reg Procedure and SigmaPlot 5.0.

Results and Discussion

Grain Temperature and Moisture Content. Temporal and spatial variation in grain temperature and moisture content near the surface of the grain bulk are presented in Fig. 2. Weekly mean temperature (averaged over all locations) remained near 30°C from July through early September, but was slightly lower when readings were resumed in late September and

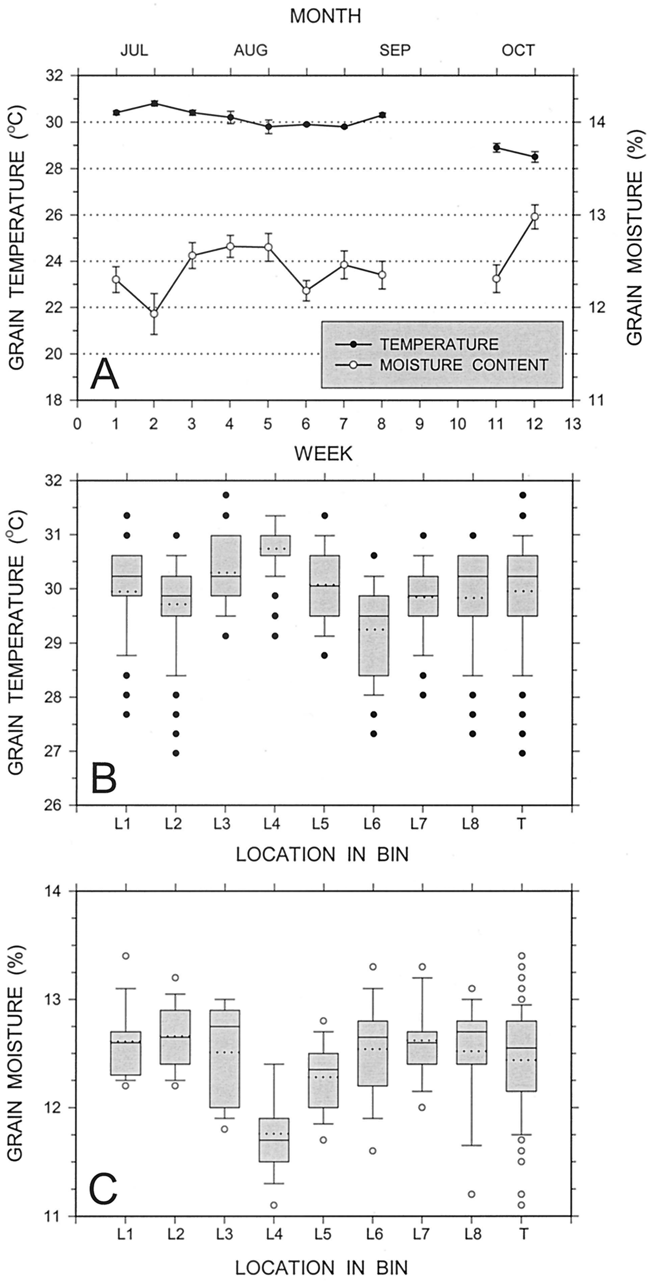

Fig. 2. Temperature (solid circles) and moisture content (open circles) of stored oats. (A) Weekly variation in mean temperature and moisture content (±SE) near the surface of the grain bulk. (B) Box plots of temperature recorded at eight locations near the grain surface over the entire storage period. (C) Box plots of moisture content, over the entire storage period, determined from grain samples taken at the same locations. The lower boundary of the box indicates the 25th percentile and the upper boundary the 75th. Vertical lines above and below the box indicate the 90th and 10th percentiles. Horizontal lines within the box indicate the median (solid) and the mean (dotted). Circles indicate outliers. T indicates the total for all locations.

early October (Fig. 2A). Mean temperature (±SD) for all locations over the entire storage period was 30.0 (±0.8)°C (Fig. 2B). Mean temperature for individual locations averaged over the storage period ranged from 29.3 to 30.7°C, and the average daily range was <0.5°C. Half of the 9,908 temperature records were between 29.5 and 30.6°C, and 80% were between 28.4 and 31.0°C. The temperature readings above and below this range, indicated by outliers in Fig. 2B, constituted 20% of the records. The minimum and maxi-

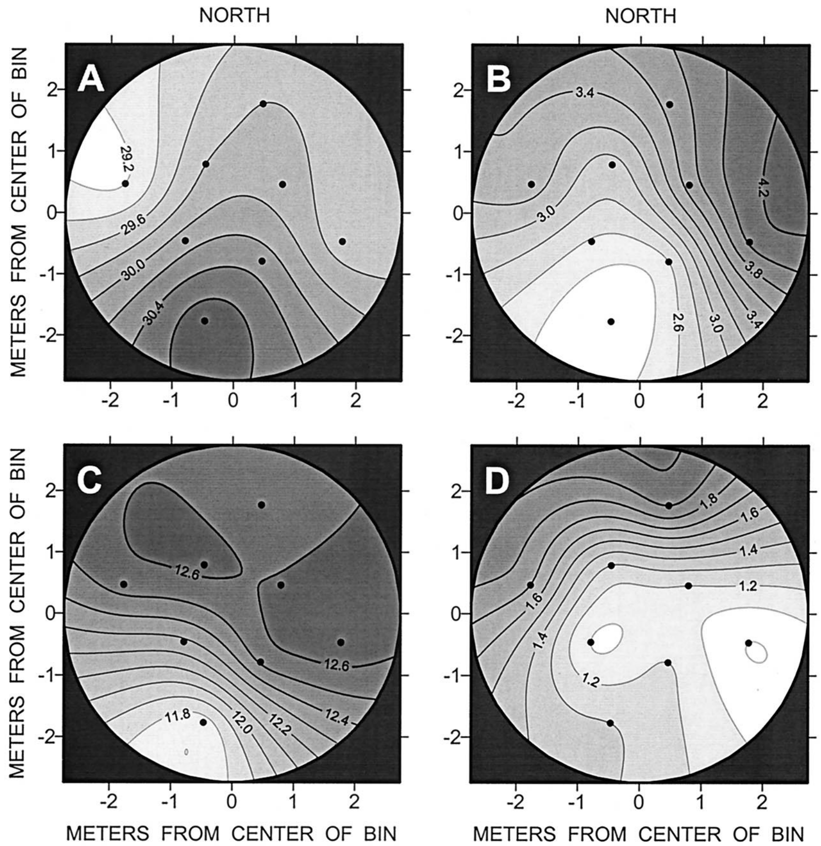

Fig. 3. Spatial distribution of temperature and moisture content in the surface layer of grain, summary for the storage period. (A) Mean temperature (°C). (B) Temperature range (°C). (C) Mean percentage moisture content. (D) Percentage moisture content range.

mum for the bin (all locations) were 27.0 and 31.7°C. Mean moisture content of the oats at the various locations ranged from 11.8 to 12.4% (Fig. 2C). Half of the 80 measurements were between 12.1 and 12.8%, and 80% were between 11.7 and 12.9%. The minimum and maximum for the bin were 11.2 and 13.4%.

When measurements were summarized over the entire storage period and analyzed spatially, weak gradients of temperature and moisture content were evident across the surface layer of grain (Fig. 3). Mean temperatures were higher in the southern half of the bin, with the highest near the south wall (Fig. 3A). The lowest temperatures occurred along the northwest wall. Temperature range was maximum in the northeast quadrant and minimum in the southwest (Fig. 3B). Moisture content was higher, and relatively uniform, over the northern half of the bin, but lower and more variable over the southern half, with the minimum near the southwest wall (Fig. 3C). Range in moisture content was maximum near the north wall and minimum near the southeast wall (Fig. 3D).

The range of temperature and moisture that prevailed in the stored oats was ideal for insect population growth, even though moisture content remained well below the critical value for storage. In a North Dakota survey, Ingemansen et al. (1986) reported that numbers of *Oryzaephilus surinamensis* (L.), *Cryptolestes* spp., and *Tribolium castaneum* (Herbst) found in stored oats increased with moisture content above 11%. Moisture is the most important factor influencing the rate at which stored grain deteriorates, and 14% is about the maximum value for safe storage (Pomeranz 1992). Above this critical value, grain respiration rates increase markedly, causing heating and spoilage. Lower moisture contents of <10% and temperatures below 15°C are required to prevent population growth of stored grain insects (Sinha 1973). For most species, optimum temperatures lie between 25 and 35°C (Sinha and Watters 1985).

The Insect Population. Trap captures of insects for the storage period were not equally distributed among locations (χ^2-test, $P < 0.01$), but the degree of variation was moderate (Fig. 1B). These captures indicated an adult insect population that included at least 31 species, or higher taxa that were not identified to species (Table 1). Most of these were either granivorous or fungivorous species, or predators and parasitoids of these species, that have been recorded frequently from stored grain. A few, such as the scarab beetle *Atenious simulator* (Harold), are typically

Table 1. Insects captured by grain probe pitfall traps in oats stored during the summer and fall of 1996 at a seed processing plant in north-central Florida

Taxon	Abbreviation
Collembola	Coll
Psocoptera	
Psyllipsocidae	
Psocathropos lachlani Ribaga	*Pl*
Liposcelidae	
Liposcelis entomophila (Enderlein)	*Le*
Heteroptera	
Anthocoridae	
Xylocoris galactinus (Fieber)	*Xg*
Coleoptera	
Staphylinidae	
Oligata parva Kraatz	*Op*
Scarabaeidae	
Ataenius simulator (Harold)	*As*
Bostrichidae	
Rhyzopertha dominica (F.)	*Rd*
Nitidulidae	
Carpophilus dimidiatus (F.)	*Cd*
Carpophilus freemani Dobson	*Cfr*
Rhizophagidae	
Europs sp.	*Eur*
Monotoma longicollis Gyllenhal	*Mlo*
Monotoma picipes Herbst	*Mp*
Silvanidae	
Ahasverus advena (Waltl)	*Aa*
Ahasverus rectus (LeConte)	*Ar*
Cathartus quadricollis (Guérin-Méneville)	*Cq*
Oryzaephilus surinamensis (L.)	*Os*
Laemophloeidae	
Cryptolestes ferrugineus (Stephens)	*Cf*
Crytolestes pusillus (Schönherr)	*Cp*
Languriidae	
Cryptophilus integer (Heer)	*Ci*
Lathridiidae	
Corticaria sp.	*Cort*
Tenebrionidae	
Alphitobius laevigatus (F.)	*Al*
Palorus subdepressus (Wollaston)	*Ps*
Tribolium castaneum (Herbst)	*Tc*
Mycetophagidae	
Litargus balteatus LeConte	*Lb*
Typhaea stercorea (L.)	*Ts*
Colydiidae	
Myrmechixenus latridioides Crotele	*Ml*
Anthicidae	
Anthicus floralis (L.)	*Afl*
Curculionidae	
Sitophilus oryzae (L.)	*So*
Sitophilus zeamais Motschulsky	*Sz*
Hymenoptera	
Pteromalidae	
Theocolax elegans (Westwood)	*Te*
Bethylidae	
Plastanoxus westwoodi (Kieffer)	*Pw*
Diptera	
Drosophilidae	Dros

found in other habitats, and their occurrence in stored grain was certainly accidental. *Ahasverus rectus* (LeConte) occurred in small numbers (three were trapped). This species is widely distributed in the southeastern states and has been considered a field insect that may contaminate stored food products (Zimmerman 1987). The staphylinid *Oligata parva* Kraatz has previously been recorded from stored grain, where it is believed to prey on mites (Hinton 1945). No Lepidoptera were captured, but their absence in the trap samples does not necessarily indicate their absence from the stored grain, although no significant populations were noted. Grain probe traps that are inserted completely below the grain surface occasionally capture a few moth larvae but rarely capture adults, and they are not effective in monitoring moth populations.

The psocid *Liposcelis entomophila* (Enderlein) and the foreign grain beetle, *Ahasverus advena* (Waltl), both of which are favored by relatively high grain moisture content, were by far the most abundant species in the traps, and together they made up 88% of the insects captured (Fig. 4). An undetermined species of *Corticaria;* the hairy fungus beetle, *Typhaea stercorea* (L.); and the sawtoothed grain beetle, *O. surinamensis,* made up an additional 8%. The first two of these are also favored by high moisture content, as is the next most abundant species, the corn sap beetle, *Carpophilus dimidiatus* (F.). *L. entomophila* occurs primarily in stored grain and in biological collections in the southeastern and midwestern United States (Mockford 1993). Both larval and adult stages of Lathridiidae, to which the genus *Corticaria* belongs, feed on fungi, especially molds, and those that occur in warehouses and granaries do not cause any direct damage to stored commodities (Hinton 1945).

The weekly number of insects trapped remained low and nearly constant for the first 3 wk after storage and initial fumigation, then increased weekly until the oats were again fumigated (Fig. 5A). When trapping was resumed 2 wk after the second fumigation, the number of insects captured indicated a marked reduction of the insect population, but trap catch during the third week following fumigation showed a strong population resurgence. The number of insects captured during this week was ≈64% of the number captured just before fumigation and most of the insects captured were psocids (Fig. 5 A and B), indicating that the resurgence was caused largely by a strong and rapid recovery of the psocid population. Other species, such as *A. advena, Corticaria* sp., *T. stercorea,* and *C. dimidiatus,* also survived the fumigation but did not rebound like the psocids (Fig. 5 C–F), and trap captures of some (Fig. 5 D and E) showed significant population decline even before the fumigation. Failure of the second fumigation to eliminate the infestation can be attributed in part to the way it was done and to uneven penetration of the gas into the grain bulk. Spatial analysis of the psocid population before and after fumigation suggested the presence of refuges that permitted part of the population to survive, and these probably occurred where concentrations of fine material filled the intergranular space and impaired gas penetration (Arbogast and Mankin 2000).

Spatial distribution of insects in stored grain could be influenced by many factors. Because insects show oriented responses to temperature and moisture gradients (Amos 1968, Amos and Waterhouse 1969, Arbogast and Carthon 1972, Perttunen 1972, Arbogast 1974) and to the distribution of dockage (foreign material, broken grain, and fine farinaceous material) (McGregor 1964), we would expect these to be among

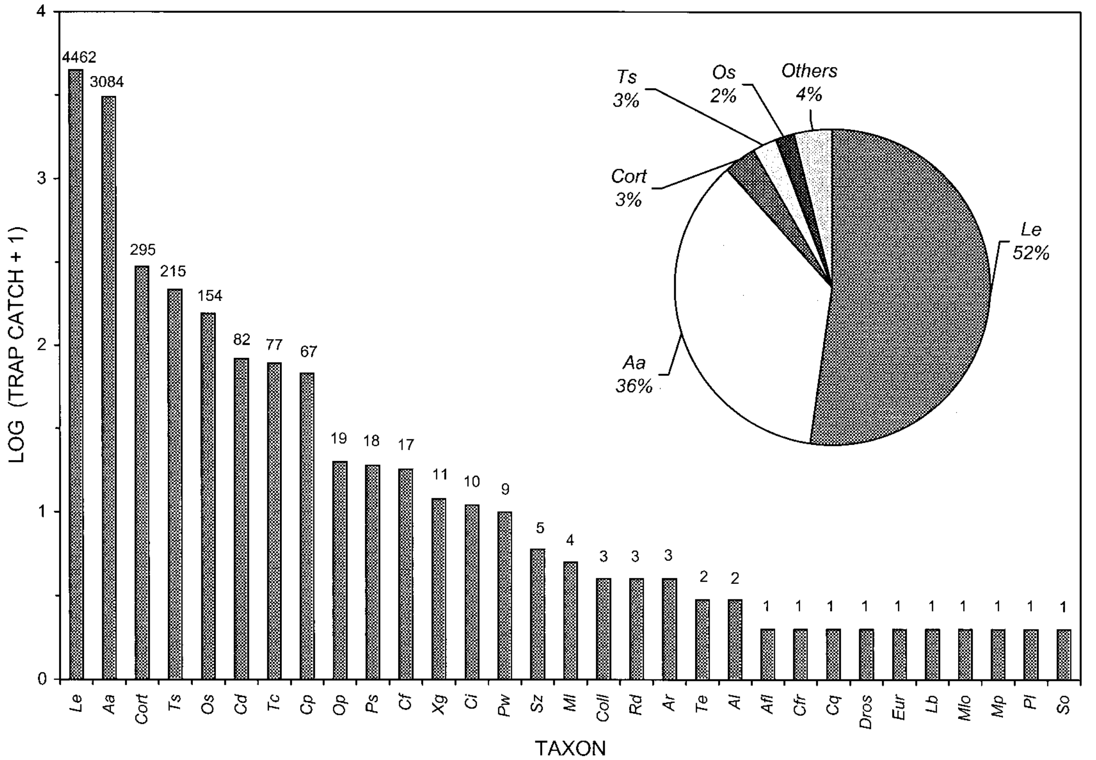

Fig. 4. Distribution of trap catch (abundance) by species (or higher taxa) and species composition (inset) of the insect population. The numbers above the bars give the total number of each taxon captured. For explanation of abbreviations, see Table 1.

the major factors determining insect distribution in stored grain. Contour analysis of trap catches indicated that, at their highest population levels, beetles were concentrated along the wall of the bin from northwest to east (Fig. 6A), so that the largest trap catches coincided roughly with the highest moisture contents (Fig. 3C). This pattern was determined largely by the distribution of *A. advena* (Fig. 6B), which made up >75% of the beetle population. The next most abundant beetle, *Corticaria* sp., which made up only ≈7% of the beetle population, showed a somewhat different distribution, but still the largest trap catches occurred mostly in the area of highest moisture content (Fig. 6C).

The distribution of *L. entomophila* captures (Fig. 6D) was almost the inverse of the beetle distribution, which raises some interesting questions. First, is this inverse relationship real, or is it an artifact of the sampling procedure? Second, if the relationship is real, what is the cause? The movement of beetles within traps could well have destroyed many psocids before the traps were emptied, especially when beetles were numerous, and this could create the illusion of inverse spatial patterns. However, a real population process (such as predation by *L. entomophila* on beetle eggs or differing responses to temperature, moisture, and dockage) could be responsible. At least one case of a psocid, *Liposcelis bostrichophilus* Badonnel, consuming beetle eggs has been reported in the literature (Williams 1972). The area in which most psocids were captured approximated the area of highest mean temperatures (cf. Figs. 3A and 6D), and the area of maximum capture occurred near the spoutline. The spoutline is a region high in dockage that forms under the loading spout as the bin is filled, because lighter material does not flow as far and so remains near the center of the bin (Hoseney and Faubion 1992).

Evaluation of EGPIC. We used only the last four (weeks 7, 8, 11, 12) of the weekly data sets to evaluate EGPIC, because earlier automatic counts were incomplete. Nighttime captures were not recorded during the first 6 wk, because workers at the plant turned the lights on and off each day by means of a circuit breaker, which also turned the EGPIC system on and off. This practice was discovered and corrected after 6 wk, and only the data from the remaining four samples was evaluated.

In theory, the manual insect counts and the corresponding automatic counts recorded by EGPIC should be identical, and each should equal exactly the number of insects captured by the pitfall in the course of a week. However, the observed counts were never identical. The mean percentage error (±SE) for the 4-wk period was 11.1 (±7.1%), but the mean gives a deceptively low indication of error because positive and negative errors tend to cancel. We can gain a

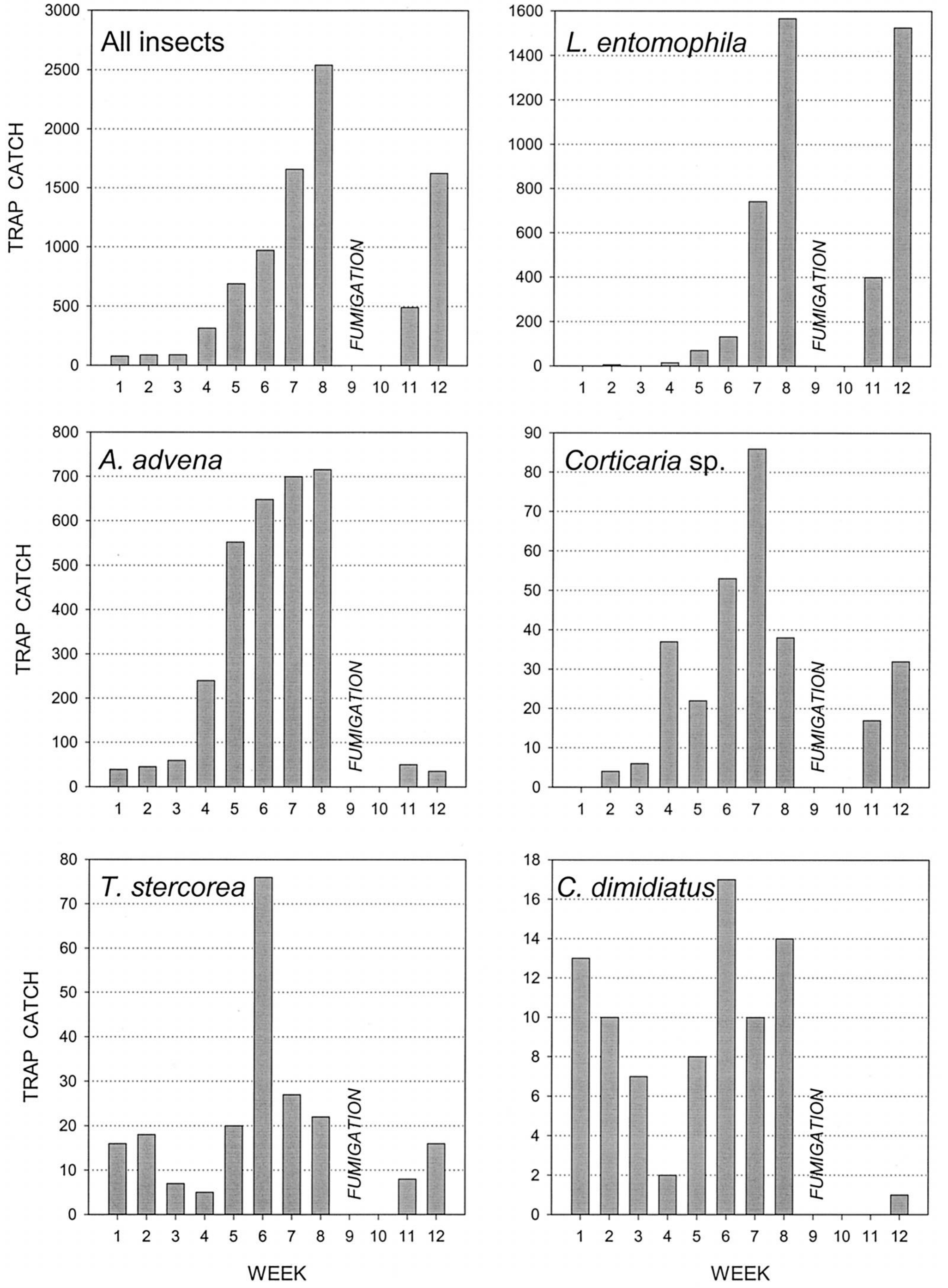

Fig. 5. Temporal distribution of trap catch (abundance) of all insect species combined and of *L. entomophila, A. advena, Corticaria* sp., *T. stercorea,* and *C. dimidiatus.*

better indication of error by averaging the absolute values of the errors and by examining the statistical distribution of the individual errors, which showed both over- and undercounting (Fig. 7A). The mean (±SE) of the absolute values was 31.7 (±4.3), and individual errors ranged from −79.4 to 82.4%, with half falling between 8.5 and 30.0%. The mean difference between manual and automatic counts differed significantly from 0 (Wilcoxon Signed Rank test, Signed Rank = 114, $P = 0.01$).

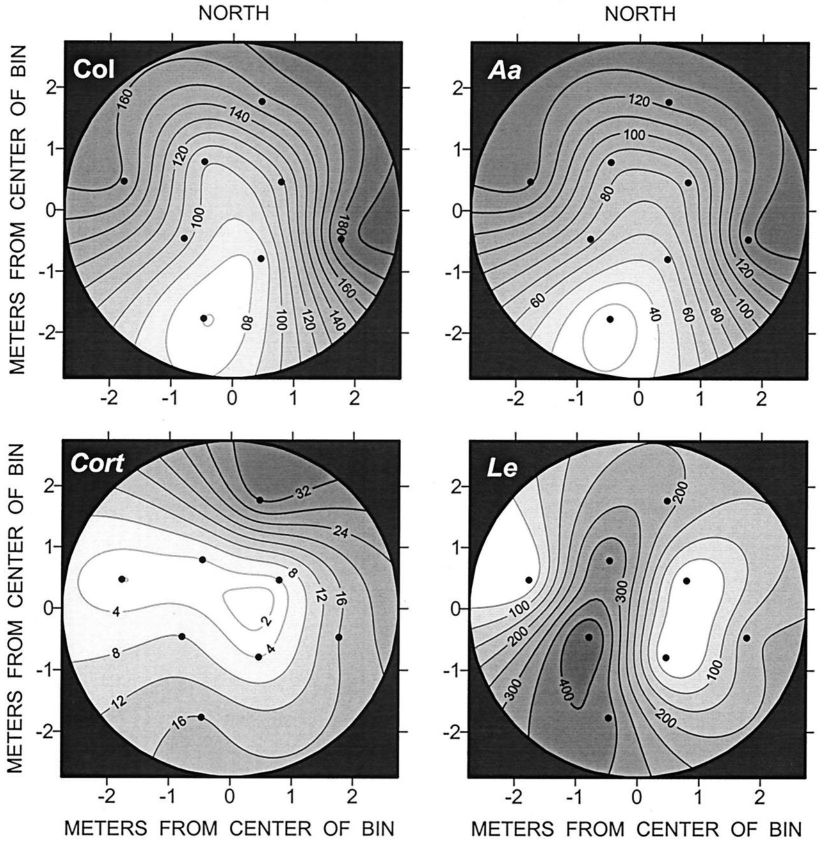

Fig. 6. Spatial distribution of all beetles combined (Col) and of *A. advena* (*Aa*), *Corticaria* sp. (*Cort*) and *L. entomophila* (*Le*) when the numbers captured were highest. This was week 7 for *Corticaria* sp. and week 8 for all the others.

Errors in the automatic counts, which we define as the difference between a manual count and the corresponding automatic count, can be attributed to a variety of factors. We have assumed tacitly that the manual counts are exactly equal to the number of insects captured by the pitfalls in the course of a week. Actually, the manual counts are sometimes only approximations of the numbers captured, because captured insects may be destroyed before they can be removed from the traps as noted in our discussion of *L. entomophila.* One significant source of error in the Williston test was failure of EGPIC to count small individuals of *L. entomophila* (which would tend to compensate for those destroyed). The sensitivity of the EGPIC system had been set to ignore minute arthropods such as mites, but to count small insects such as *Cryptolestes.* Unfortunately, the large population of *L. entomophila* included many individuals smaller than *Cryptolestes* but larger than most grain mites, and there is no way to determine how many of these were counted. Other sources of error included dockage particles small enough to be carried into the traps by insect activity and large enough to be counted, insects falling through the detector in close proximity or clinging together, generation of spurious counts when cables were disturbed, and corrosion of contacts by phosphine fumigation.

Although the manual (m) and automatic (a) counts were not equal, regression analysis showed a significant linear relationship between them. $m = (28.8 \pm 24.9) + (1.02 \pm 0.1)a$ ($F = 57.2$, $P < 0.01$, $R^2 = 0.68$, Adjusted $R^2 = 0.67$). The intercept (28.8) did not differ significantly from 0 ($F = 1.34$, $P = 0.26$), and furthermore, there is a good theoretical basis for taking the origin as a point on the regression line with no sample variation, because when no insects are captured, $m = a = 0$. Thus, the confidence interval for regression through the origin converges to 0 as m and a becomes smaller. The regression line (Fig. 7B) is $m = (1.15 \pm 0.08)a$ ($F = 198.4$, $P < 0.01$, $R^2 = 0.88$, Adjusted $R^2 = 0.87$). The broad 95% prediction interval (Fig. 7B) indicates low precision in predicting numbers of insects captured (manual counts).

In conclusion, the data sets generated by the Williston field study will find application in population modeling and development of integrated pest management systems for stored grain. They will also be useful in developing improved monitoring devices for detecting infestations and estimating infestation levels, especially electronic devices for automatic mon-

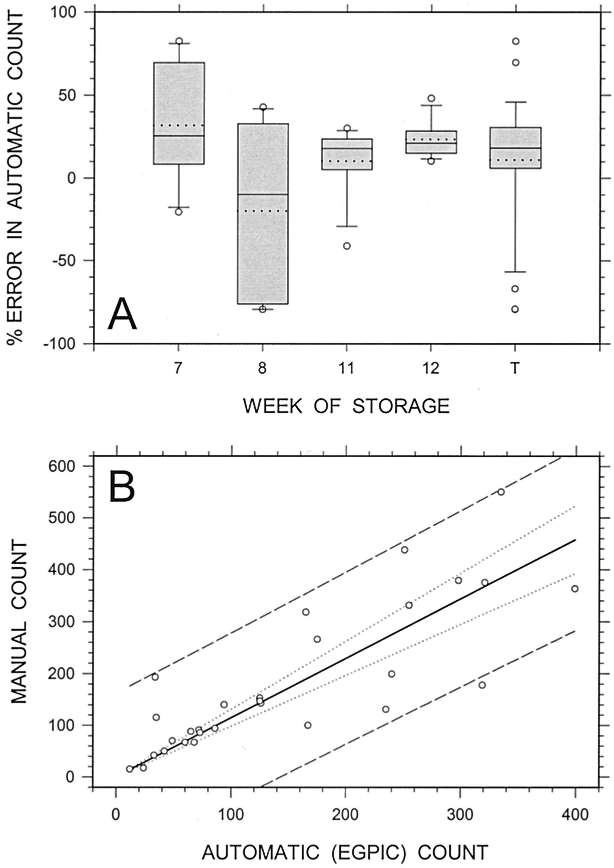

Fig. 7. Number of insect captures recorded by EGPIC during 1-wk trapping periods in stored oats. (A) Box plot of captures for weeks 7, 8, 11, 12, and total (T) for all four periods combined. Lower and upper box boundaries indicate 25th and 75th percentiles. Solid and dotted horizontal lines indicate medians and means. Lower and upper vertical lines indicate 10th and 90th percentiles. Circles indicate outliers. (B) Relationship of manual to automatic (EGPIC) counts shown by regression through the origin. Dotted lines indicate 95% CL, and dashed lines indicate 95% prediction limits.

itoring. These devices must not only be sufficiently robust to withstand the harsh conditions encountered in commercial grain storage facilities, but also must be able to count and record accurately the number of insects captured (or otherwise detected). The diversity of insect species found in many facilities, especially in the southeastern states (Arbogast and Throne 1997), the often wide range of sizes within species, the high population levels sometimes attained, and the presence of small dockage particles are all major challenges to accuracy.

Even when an accurate count is achieved, we are still faced with the problem of interpreting the count in terms of pest population density or in terms of some required action. Federal grain inspectors assign the special grade "Infested" to grain on the basis of numbers and types of insects found in a 1-kg sample (USDA 1997). It is essential that dockage particles be excluded from recorded counts, and effective pest management with minimum use of pesticides requires identification of the species, or at least the genera, of insects captured. Recent advances in the application of near-infrared spectroscopy to detection and identification of stored grain insects (Dowell et al. 1998, 1999) offer a theoretical basis for accomplishing this. A near-infrared detector, in conjunction with appropriate computer software, could conceivably accept, reject or partition counts according to the chemical composition of the objects generating them.

The errors observed with the version of EGPIC tested at Williston were too large for the practical purpose of making management decisions in commercial grain storage facilities, but the test uncovered weaknesses in the system that can be corrected by additional research and development. An improved version of the EGPIC probe was recently evaluated in the laboratory (N. D. Epsky and D.S., unpublished data) and will soon be tested under commercial storage conditions.

Acknowledgments

We are indebted to W. J. Rees (Williston Seed Processors) for making his facilities available for research and for his cooperation in the field test. We are especially grateful to S. Chini for her untiring assistance in tabulating and analyzing data and preparing figures, and for her many valuable suggestions. We thank K. Coggins and P. Sun for their valuable assistance in the field, and L. Sparks for technical assistance in the laboratory. We are indebted to the systematists who identified and provided information on some of the insects captured: M. C. Thomas (Division of Plant Industry, Florida Department of Agriculture and Consumer Services, Gainesville,) identified specimens of Scarabaeidae, Anthicidae, Rhizophagidae (*Europs*), Cucujidae (*A. rectus*), Lathridiidae, and Colydiidae; E. L. Mockford (Department of Biological Sciences, Illinois State University, Normal) identified specimens of Psocoptera; and J. H. Frank (Department of Entomology and Nematology, University of Florida, Gainesville) identified specimens of Staphylinidae. Finally, we express our appreciation to J. E. Baker, N. D. Epsky, and M. A. Mullen for their critical review of an early version of the manuscript and for their helpful suggestions.

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Received for publication 13 October 1999; accepted 5 March 2000.